APPENDIX B

Potential for Lime and Sludge Reduction by Bunker Hill Mine Water Mitigation Measures

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Potential for Lime and Sludge Reduction by Bunker Hill Mine Water Mitigation Measures

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Summary

Bunker Hill mine water acid production occurs primarily in the pyrite-rich Flood-Stanly Ore Body. Discharge from the Flood-Stanly Ore Body represents only about 9 percent of the flow but carries more than 90 percent of the metal load from the mine. Application of mitigation options to reduce the amount of surface water infiltration into the Flood-Stanly Ore Body should reduce lime consumption and sludge production at the mine's Central Treatment Plant (CTP). The amount of reduction cannot be accurately estimated because of the complexity of both the surface water infiltration and mine water flow paths. Implementation of Flood-Stanly Ore Body inflow mitigation measures is expected to reduce seasonal peak lime consumption and sludge production more than seasonal base flow conditions. This is because lime consumption is controlled more by flow than by metals concentrations, using historical (1983 to 1988) and recent data (1998 and 1999) as a basis of judgement. Furthermore, documented historical large flow events typically have a sharp rise to a peak and relatively rapid fall with a short overall duration from a few days to perhaps a few weeks.

Available data strongly suggest that accumulation of metal-bearing salts has not occurred in the mine to date. Field observation underground and the lack of dissolution-related hysteresis at monitoring station 9LA demonstrate this. However, if mitigations are constructed there may be a possibility of accumulation of soluble metal-bearing sulfate salts as a result of decreased periodic flushing. If this occurs, it may take several years to accumulate a significant amount of salts. The potential for accumulation should be monitored, although significant portions of the ore body are currently inaccessible. Assuming significant accumulation did happen and a large in-mine flow event occurred that dissolved the salts, there would be high acid and metal loads that could stress or overwhelm treatment capacity. The extreme events could be handled either by diversion into the mine pool for later treatment, or treated in a CTP that has sufficient capacity.

Mitigation effectiveness must be monitored, particularly in the West Fork Milo Creek (West Fork Milo Creek), which overlays the Flood-Stanly Ore Body. This should include surface

water, piezometer water levels, and in-mine water monitoring. At a minimum, in-mine monitoring should include stations 9LA, 9PU, and 9KT, although other more mitigation-specific locations are desirable.

1.0 Introduction

The purpose of this memorandum is to evaluate whether significant reductions in lime consumption and sludge generation will result from the construction of mitigation measures to reduce recharge to the Bunker Hill Mine. As described in more detail in the following sections, reducing the surface water recharge in the West Fork Milo Creek could serve two purposes: a) keeping surface water from contacting metal-bearing minerals and subsequent metal leaching (keeping clean water clean), and b) reducing the water volume infiltrating into the mine. The basic tenet is that by reducing the amount of water infiltrating into the mine, particularly the Flood-Stanly Ore Body, not only is the amount of water needing treatment reduced, but this reduction should also reduce metals concentrations and sludge production.

2.0 Conceptual Model

The conceptual model of acid water production and drainage from the underground workings of the Bunker Hill Mine has been described in a number of documents (see Section 7.0, Cited References). This section of the report is a brief summary of this published information.

The production of acid drainage from an underground mine requires the presence of three contributing components: oxygen, sulfide minerals, and water (CH2M HILL, 1999a and 1999b). Oxygen is present in non-flooded portions of a mine because of the naturally circulating mine atmosphere through the mine workings down to the mine pool water elevation (between the 11 and 12 levels). Water is present because of recharge at land surface from snowmelt runoff and rainfall within the area of influence of the mine and the extensive mine workings that create a large drawdown of the water table (particularly in the West Fork Milo Creek drainage at Bunker Hill). Water is also available as water vapor in the mine atmosphere, which is saturated or near saturation in most areas. Sulfide minerals are present in varying abundance in most metal mines but occur in higher concentrations within and adjacent to specific ore bodies.

The Bunker Hill Mine hydrology is complicated by the evolution of the mining history and the complex nature of the underground workings (Trexler, 1975; Eckwright, 1982; Riley, 1990). The mine was initially developed at higher elevations within the Milo Creek drainage with shallow workings along near-surface ore bodies. The individual workings were combined into a single mine with numerous working levels (on approximately 200-foot vertical spacing) to considerable depths. Shortly after 1900, the Kellogg Tunnel was constructed from a much lower elevation (9 Level) to allow more efficient transport of men and materials. All mine water discharges from the Kellogg Tunnel. The mine was then developed down from 9 Level (Kellogg Tunnel level) to 30 Level. A tunnel was constructed on 23 Level to connect the Bunker Hill Mine with the nearby Crescent Mine. The configuration of adits, tunnels, and other mine workings make it essentially impossible to flood the mine workings above 9 Level because there are so many adits and near-surface stopes above 9 Level. These workings would discharge acidic water if the Kellogg Tunnel were flooded.

The 9 and higher levels, called the upper country of the mine, have additional surface openings that would make mine sealing very difficult. The mine workings, from about 30 feet below 11 Level, are currently flooded, causing the formation of a mine pool. The water level is currently maintained by pumping water from the pool that is measured at the 9PU monitoring station.

Studies conducted at the University of Idaho in the 1970s and 1980s show that most of the acidic water containing elevated concentrations of metals originates in the Flood-Stanly Ore Body in the upper country of the mine (Trexler, 1975; Riley, 1990). This conclusion has been confirmed by data collected in the 1998-1999 period in which the pH ranged between 0.59 and 3.9 at monitoring stations that measure drainage from the Flood-Stanly Ore body. The mineralized zone extends from near land surface downward to and beyond 9 Level. Most of the ore body has been mined but has been backfilled with sulfide-rich gob. Gob is material containing zinc, lead, and iron sulfides that was non-economic to recover during the early years of mining. Mining within the Flood-Stanly Ore Body facilitated acid water production by exposing acid-producing minerals to oxygen and water. In addition, the mining created zones of very high vertical hydraulic conductivity, which allows flushing of the acid reaction products to lower portions of the mine. Oxygen has been, and will continue to be, available within most of the Flood-Stanly Ore Body because of the numerous open stopes, transfer chutes, and other workings that intersect the ore body.

The block caving mining method used within the Flood-Stanly Ore Body during the 1940s and 1960s further complicates the acid water drainage problem. Caved mineralized zones and fracturing associated with this mining technique extend to land surface. The major surface depression caused by the block cave mining is called the Guy Cave Area, and occurs near the bottom of the West Fork Milo Creek drainage. Cracking caused by the caving extends to the surface and provides a major conduit for surface water infiltration into the Flood-Stanly Ore Body. In addition, surface water infiltrates into the mine workings in much of the Milo Creek area through other mining-related conduits and the subregional groundwater system, thus forming the third component required for acid water production.

In summary, acid water containing elevated concentrations of metals drains from the Bunker Hill Mine because the underground workings provide the required components for the production of acid water and both the dissolution and transport of elevated metals concentrations. The subregional groundwater system provides recharge of carbonate-buffered water to the mine through natural fractures in the unmined metamorphic rocks surrounding mineralization. Most of the recharge to the mine and the acid-producing ore body in particular is via man-made openings. The recharge to the mine from undisturbed rock is very small.

Water from the annual surface water runoff/infiltration event associated with spring snowmelt and streamflow moves through the upper country mine workings, dissolving acid salts from oxidizing sulfide sites and moving ponded acid water from within the mine drifts. Most of the drainage from the upper country workings discharges on 9 Level and drains out the Kellogg Tunnel. The quantity that drains from the Kellogg Tunnel is

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relatively well-documented, but an unquanitified portion of the water from the upper workings bypasses 9 Level to discharge on levels 10 and 11 and ultimately into the mine pool. Comparison of mine pool temperature measurements with the believed geothermal gradient suggests that this upper country recharge impacts the 12 Level mine pool water but probably has little impact on the mine pool water below 13 Level. This implies little mixing of the upper country water into the deeper pool. Rather, the upper country recharge is thought to flow across the upper pool toward the extraction pumps, which maintain the pool level at about 30 feet below 11 Level at Raise No. 2.

Water chemistry varies greatly from site to site within the Bunker Hill Mine. The drainage from the Kellogg Tunnel represents the collection of water of varying quantity and chemistry from throughout the mine. Several generalizations can be made. First, most of the poor quality water originates within the upper country portion of the Flood-Stanly Ore Body. Second, flushing of the upper workings during spring recharge events causes higher metal concentrations with higher flows at the CTP. Thus, the highest metal loading from the mine occurs in the spring and early summer and is related to infiltration of snowmelt runoff and flushing of the mine workings. Water movement through the Flood-Stanly Ore Body causes the greatest increase in metals concentrations.

3.0 Hydrogeologic Setting

The following text provides detailed information on the mine geology and hydrology.

3.1 Geology and Mine Development

The Bunker Hill Mine is located in the Kellogg-Wardner area within the South Fork Coeur d'Alene (SFCdA) River drainage basin of northern Idaho. The Bunker Hill Mine is one of many located within the Coeur d'Alene mining district.

The principal rock types found in the Coeur d'Alene mining district belong to the Belt Supergroup of Precambrian metamorphic rocks (Hobbs et al., 1965; Riley, 1990). They are composed of fine-grained argillites and quartzites associated with smaller amounts of carbonate-bearing dolomitic rocks. The formations of the Belt Series from oldest to youngest are Prichard, Burke, Revette, St. Regis, Wallace, and Striped Peak.

The Coeur d'Alene mining district lies at the intersection of a broad arch that extends from Kimberly, British Columbia, to the St. Joe River in Idaho and the Lewis and Clark Lineament (Trexler, 1975). The Lewis and Clark Lineament is represented in the district by the Osburn and related faults. The patterns of the folds and faults in the district are governed by the Osburn Fault, an extensive fault with a west-northwest strike and a large strike-slip displacement. Movement along the Osburn Fault is right lateral with a maximum displacement of 16 miles.

The faulted block of Belt Series sediments that includes the Bunker Hill Mine lies south of the Osburn Fault and contains several additional major faults. Major faults intercepted in the Bunker Hill Mine include the Cate, Sullivan, Dull, Katherine, Buckeye, and Kruger. These major faults make up the skeleton along which the ore bodies are associated. The Cate Fault is the major structure in the mine, striking northwesterly and dipping 40 to 60 degrees to the southwest. The Sullivan, Dull, and Kruger faults lie in the foot wall (northeast) of the

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Cate Fault. The Katherine and Buckeye faults lie in the hanging wall (southwest) of the Cate Fault. All these faults strike more westerly than the Cate, with a dip of 50 to 30 degrees to the southwest.

The Bunker Hill Mine itself is located within a highly faulted block of transition rock between the Revette and St. Regis formations. The Revette formation is composed primarily of massive quartzites interlaminated and interbedded with argillites. The St. Regis formation includes argillites and argillaceous quartzite, which grade downward to the base into nearly pure quartzite.

The Bunker Hill Mine includes three general ore types based on mineralogy. Trexler (1975, p. 23-24) describes them as follows.

> "The Bluebird ore contains considerable pyrite and galena, which usually exceeds or equals sphalerite in a siderite-quartz gangue. The Bunker Hill ore consists mainly of galena in a siderite-quartz gangue. The Jersey ore consists of galena with considerable sphalerite in a quartz-siderite gangue. The major mineralogical difference between the three ore types is the presence of large quantities of pyrite in the Bluebird ore and the high degree of oxidation found in the Bluebird ore areas (upper levels of the mine)."

Carbonate gangue minerals can provide significant neutralization capacity. Siderite, a ferrous carbonate gangue [$FeCO_3$ when pure], is a common accessory to the ore minerals (Kroll, 1935, Hobbs et al., 1965). Unfortunately, the ferrous iron in siderite will oxidize and hydrolyze, overcoming the neutralization of the carbonate:

$$FeCO_3 + {}^{1}/_{4}\, O_2 + {}^{5}/_{2}\, H_2O \Rightarrow Fe(OH)_3 + HCO_3 + H^+$$

The amount of helpful carbonate buffering will depend on the amount of ankerite, calcite, and dolomite in the gangue minerals. These quantities are not known.

The ores occur along major faults with little dispersion out into the country rocks. The mine was developed with levels on about 200-foot-elevation intervals generally following the structural features associated with the Cate Fault. Thus, the shafts are inclined, with workings generally following a strike to the northwest and a dip of about 60 degrees to the southwest. The main entrance to the mine, the Kellogg Tunnel, was constructed from the valley of the SFCdA River to the underground workings on 9 Level. Historically, mining has occurred from near land surface on the 3 and 4 levels to below 30 Level.

3.2 Mine Hydrology

Water flow in and near the Bunker Hill Mine reflects the intentional and unintentional impact of mining activities on the regional bedrock groundwater flow system. Trexler (1975), Eckwright (1982), Hunt (1984), Erikson (1985) and Riley (1990) provide detailed information on water flow in and near the mine from a series of studies conducted by the University of Idaho. Eckwright (1982, p. 24) divides the occurrence and movement of water within the mine into two groups.

> "1) water movement that occurs through man-made openings from the surface to the underground mine levels and from level to level down through the mine, and

> 2) water discharged into the mine from natural fracture systems in the rock either through drill holes or directly into drifts and stopes."

Trexler (1975, p. 54) describes the development of the mine and the impacts on water flow patterns as follows:

> "After the mining began in 1885, the equilibrium of the ground-water system in the mine area was disturbed. Often the stopes were worked to the surface, some even into the creek bed. This caused increased recharge through stopes and increased discharge from the portals. The Milo Creek area (Small Hope and East Reed workings) and the Deadwood Creek area (Inez, Arizona and Oakland workings) are excellent examples of such a disturbance.
>
> As the mining activity extended downward from the upper levels, a vertical zone of high permeability was developed. The porosity is secondary, formed from multilevel stopes and other interconnections, man-raises and ore passes.
>
> Block caving, used in the upper levels (4, 5 and 6) of the Bunker Hill Mine, forms another vertical zone of high permeability. The surface depression caused by the subsidence brought about by the caving creates a major surface recharge site. This surface feature channels three small intermittent tributary valleys of Milo Creek directly into the caved area where the water freely moves on down through the old workings."

The mine workings interconnect the pre-mining subregional groundwater system almost exclusively through fractures within the block caving imposed by the mining methods. These subregional groundwater system fractures are hydraulically connected to the Milo Creek drainage.

Much of the water draining by gravity through the mine workings is captured on 9 Level and drains out the Kellogg Tunnel. Water currently not captured from the upper workings and water from the lower workings is pumped up to 9 Level to join the upper country drainage. The pumping maintains the mine pool water level between the 11 and 12 levels. Riley (1990) indicated in the 1980s that about 44 percent of the Kellogg Tunnel discharge was gravity drainage, with the remaining 56 percent pumped from the lower workings.

Both Trexler (1975) and Riley (1990) document flow changes in the mine related to annual recharge events. The flow is most sensitive to snowmelt runoff, and higher discharges are most dominant at sites in the upper country portion of the mine.

Hunt (1984) studied recharge within portions of the Milo Creek watershed. He concluded the following (page 65):

> "All of the flow from West Milo Creek drainage enters fracture flow systems which ultimately discharge into the mine.
>
> Other probable areas of recharge to flow systems feeding the mine are: near the South Milo-Cate Fault intersection, the area of cottonwoods in Milo Creek below Milo Creek Dam, along the south bank of Milo Creek near its Cate Fault intersection, and along other stream-fault intersections."

The authors cited above state that reduction of recharge to the Bunker Hill Mine is a viable remedial option for reducing the acid mine drainage (AMD). The specific areas where mitigation activities were recommended are those outlined above by Hunt.

In summary, the Bunker Hill Mine workings have created a large zone of drawdown in which the subregional groundwater system is dominated by unsaturated flow conditions but with numerous small perched and saturated zones. Recharge occurs as a result of sub-regional groundwater flow systems and seasonal snowmelt/rainfall/recharge. The sub-regional system is generally expressed by long-term, fairly steady flow within the mine. Seasonal phenomena are expressed by short-term peaks (a few days to a few weeks) in the hydrologic record. The peaks usually involve only a few days but the falling limb of the hydrograph can take a few weeks. The peak flows indicate movement of water rapidly from a surface source (probably streamflow) through the upper workings. The peak flows cannot originate from groundwater flow systems in undisturbed rock. Groundwater collected by the upcountry mine workings predominantly moves through the workings in a series of cascading ditch flow systems. These flows converge and currently discharge from the Kellogg Tunnel and are treated.

3.3 Water Flow in the Mine

Flow measurements taken at several points in the mine (Level 3HD, 5BK, 5WM and 5WR, 9VR, 9SX, 9SO, 9CR, 9LA, 9BS, and 9BO) during the snowmelt runoff in 1999 indicate that peak flows occur first on 5 Level (March 11 to 17 for 5BK and 5WR, March 31 for 5WM), followed by April 2 for 9BS; April 29 for 3HD; May 28 for both 9SO and 9CR; and June 4 for 9SX, 9LA, and 9BO. These time differences suggest that different parts of the mine receive recharge from snowmelt runoff at different times, which underscores the complex hydraulic connections within the mine. Also, 9 Level receives flow from the upper levels. Some of the lag times result from delays caused by water movement within the mine.

A comparison between historical (1983 through 1988) and more recent and current data (1998 and 1999) indicates that the timing of peak flows for most stations has not changed appreciably (CH2M HILL, 2000). The timing of flow peaks is essentially the same for 3HD and 5WR. Flow peaks and base flow at 5BK and 5WM are very similar. These results suggest that recharge quantities along the main stem of Milo Creek have not changed substantially in recent years. Similarly, the conditions at 9BO are similar and indicate that discharge from the drill hole on 7 Level has not changed. Flow at 9BS is also very similar between the historical and current data, indicating that recharge from Deadwood has not changed substantially. However, stations downgradient of and receiving flow from the Flood-Stanly Ore Body (9CR, 9SO, 9SX and 9LA) have shown that even though base flow conditions have essentially not changed, there has been an increase in peak flows by a factor ranging between 2 and 12. The timing of the 1999 peak flows through the Flood-Stanly Ore Body coincides with the onset of high elevation snowmelt and observed infiltration near the hanging wall of the Guy Cave Area near the bottom of the West Fork Milo Creek. The rising and falling limbs of the hydrographs are steep and the duration of peak flow short (a few days). These relationships suggest a direct flow path for infiltrating West Fork surface water through the Flood-Stanly Ore Body into the mine workings.

These measured differences in peak flows at 9CR, 9SO, 9SX, and 9LA may be a result of a higher runoff and higher flows in the West Fork Milo Creek, which resulted in water reaching further down the basin than that measured in the 1980s data. Joel Hunt (1984) reported that during field measurements in 1984 the lowest the West Fork flows were observed before they disappeared into the ground was 220 feet upstream from Phil Sheridan Raise No. 2. During the spring of 1999 the West Fork Milo Creek flows were observed to reach the Phil Sheridan Raise No. 2, overflow the raise because it was plugged with debris, and then flow into the ground a few hundred feet below the raise but still above the Guy Cave Area. It was during this time that the very high flows at 9CR, 9SO, 9SX, and 9LA were observed. Therefore, there may not be fundamental changes in the flow paths, only differences in observed and measured flows resulting from the size of the West Fork Milo Creek runoff and its infiltration location.

Water temperature data underground can be used to understand water movement patterns and to help locate acid-producing areas. In an undisturbed groundwater system, the water temperature generally increases with depth because of the natural geothermal gradient of the earth. The increase is about 1 degree C per 100 feet. Figure 1 (all figures are found at the end of the text) shows a plot of sample site water temperatures with depth within the mine. Data points falling on or near the geothermal gradient line reflect the expected normal groundwater temperatures. Points falling below the line (such as 9VR) probably represent conditions where water has moved rapidly down from higher mine levels. Points falling above the line probably represent heating of the water because of exothermic chemical reactions (acid water formation). Note that the 9PU site has been placed at the elevation equivalent to about 13 Level even though the pump intake is about 30 feet below 11 Level. The 13 Level is much more extensive than the 12 Level and probably is the dominant source of the 9PU discharge.

Water temperatures underground depend on several factors, principally the length of equilibration with the natural thermal gradient (increasing temperature with depth) as discussed above. A complication, however, is the heat released by the exothermic chemical reaction between water and oxidizing sulfides. Again using the 1999 water data, only the temperature of water flowing through stations 3HD and 5BK shows a slight decrease in temperature with increasing flow from snowmelt runoff. Water at all other stations increases in temperature with increasing flow. This suggests that direct hydraulic connection between the surface snowmelt runoff and the workings is probably upgradient of stations 3HD and 5BK. The hydraulic connection is either increasingly distant from the surface snowmelt runoff and/or is in direct hydraulic connection with very actively oxidizing sulfides at the other stations. A comparison of the lowest temperature for each station (base temperature) is another measure that can be used to separate hydraulic connection from oxidizing sulfide. A linear least square fit equation for the data indicates that the lowest beginning temperature of 6.2 degrees C occurs at station 5WM, followed by 9BO, 5WR, and 5BK with base temperatures of 7.3, 8.1, and 8.3 C, respectively. The next higher are 3HD and 9SX at 14.1 and 14.6, respectively. The highest is 9PU with a temperature of 16.6 C. Obviously, the combination of 3 Level and 9 Level waters having the same base temperature indicates that at least water upgradient of 3HD and 9SX involves actively oxidizing sulfides. Another indication of the effect of oxidizing sulfides on water temperatures can be seen when comparing the range of temperatures for the Stanly Ore Chute and the Stanly Crosscut. Water temperatures there range from 15-20ºC, higher than temperatures almost anywhere else in the mine (typically 5-12ºC). These temperatures reflect the greater intensity of oxidation in the Flood-Stanly Ore Body. Nevertheless, these temperatures are not in the range of 20-70ºC. Such temperatures typically promote the formation of efflorescent salts through evaporation. Furthermore, there are no dramatic excursions in temperature with snowmelt or periods of high runoff that would reflect an effect from dissolution of large quantities of salts. Hence, the temperature data support the opinion that efflorescent salts have not played a noticeable role in the mobility of metals from the Bunker Hill Mine.

4.0 Geochemistry

4.1 Controls on Acid Production

Interrelated primary factors that influence the production and distribution of AMD include both chemical characteristics:

Availability of pyrite
Sulfide oxidation - by oxygen and iron (III)
Oxidation of iron (II) to iron (III), catalyzed by bacteria
Temperature
Gangue dissolution
Lithology and mineralogy of country rock (presence of carbonate minerals)
Buffering capacity of non-mineralized groundwater
Formation and dissolution of efflorescent salts

And physical characteristics:

Recharge locations, controls, and temporal patterns
Whether groundwater flow is under saturated or unsaturated conditions
Hydraulic conductivity of the undisturbed rock
Hydraulic conductivity caused by mining activities (mine openings and mine-induced fractures)
Storage of acid water, particularly pooling in drifts
Evaporation and vapor transport for formation of efflorescent salts

Sulfides will continue to react and produce acidic products until:

Sulfides are exhausted
Oxygen is eliminated (sulfides are submerged under static water)
Water is eliminated
Reaction products are neutralized

Sulfate is the major anion in the water chemistry of the mine water. Sulfate is generated by the oxidation of iron sulfide (dominantly pyrite), which produces sulfuric acid and is described by the following chemical reaction:

$$FeS_2 + {}^{7}/_{2}\, O_2 + H_2O = Fe^{2+} + 2\, H^+ + 2SO_4^{2-}$$

The acid generated by the oxidation of pyrite attacks the associated sulfides sphalerite (zinc sulfide) and galena (lead sulfide), plus the associated carbonate gangue minerals siderite and ferroan dolomite (ankerite). Each of these minerals has impurities of other elements, occasionally at significant concentrations that are released with the major ions.

Oxidation of pyrite, sphalerite, and other sulfide minerals releases iron, lead, zinc, cadmium, and other associated metals to become part of the acid mine water. Pyrite and other iron sulfide minerals are ubiquitous major gangue (valueless) minerals associated with the ore deposit and, along with sphalerite, were typically not extracted as part of early mining operations. Based on the mine water chemistry, pyrite and sphalerite are the major sulfides in the Flood-Stanly Ore Body. Sphalerite [ideally zinc sulfide (ZnS)] likely contains most of the cadmium released to the mine water. Similar to pyrite, sphalerite oxidizes and releases zinc and sulfate and other ions to the acid mine water. Argentiferous galena was the major ore mineral recovered in the mining district and essentially the only ore mineral recovered prior to flotation. However, there is probably a remnant amount of galena still being oxidized, releasing lead, sulfate, and associated ions to the acid mine water.

Siderite, a major gangue mineral associated with ore minerals, also contains an average 0.023 percent calcium, 0.06 percent magnesium, and 0.082 percent manganese in the Coeur d'Alene mining district (Balistrieri et al., 1999). Unfortunately, there is still so much iron present that, as mentioned previously, siderite cannot offer much buffering capacity.

4.2 Relationships to Mine Workings and Water Flow Patterns

The degree to which sulfides and acidic reaction products from sulfide oxidation are available for solubilization and mobilization is directly related to the amount of air and water mixture that can contact them. Air circulation underground carries oxygen that is required for the direct oxidation of pyrite, and the support of *Thiobacillus* sp. in the catalysis of the oxidation of ferrous to ferric iron. In addition, air circulation is responsible for moving substantial quantities of water in the vapor phase. The vast majority of water flowing within the mine is relatively good quality water. Only water that contacts the pyrite/sphalerite-rich Flood-Stanly Ore Body becomes highly acidic. Approximately 100 gallons per minute (gpm) (on average) of highly acidic mine water discharges from the Flood-Stanly Ore Body; however, this small discharge mobilizes and transports essentially all of the metal load from the upper workings. **Discharge from the Flood-Stanly Ore Body represents only about 9 percent of the flow but carries more than 90 percent of the metal load from the mine.**

Some flow within the Flood-Stanly Ore Body drains past 9 Level into the mine pool, and is pumped up for discharge and treatment via the Kellogg Tunnel. Therefore, reduction in recharge to and around the Flood-Stanly Ore Body should reduce the quantity of metal that is mobilized, because a smaller quantity of water would be confined to a smaller area within the flow path.

Evaporation and circulation of water vapor can lead to buildup of efflorescent salts along the borders of ditches carrying elevated metals concentrations from AMD. This process creates metal salts that are easily dissolved when infiltration increases the water flow through the mine.

Flushing of metals generated by sulfide oxidation occurs during snowmelt recharge to the mine. This includes washing of acid salts from reaction sites, flushing of acid water pools on drift floors, and breaking of yellow boy dams within the drifts. At most in-mine monitoring locations that receive drainage from the Flood-Stanly Ore Body, an increase in flow is accompanied by an increase in metal concentration. The metal concentrations on the falling limb of the hydrograph are similar to or slightly lower than the concentrations on the rising limb. This relation between metal concentration and water discharge of the two limbs of the hydrograph is referred to as a hysteresis effect. A high level of hysteresis indicates an elevated but finite storage of soluble metals generated by oxidizing sulfides and / or ponded mine water accumulated along the mine water flowpath by a significant seasonal increase in flow.

Understanding the contribution from the hysteresis effect is important to be able to understand the storage of metalliferous reaction products and their subsequent mobilization. This understanding, in turn, is important to be able to extrapolate observed metal flux and predict plausible future flux characteristics. Interpretation of these and other relations could help in understanding current and historical data and what may occur as a result of a major infiltration event.

4.3 Analysis of Mine Data

Historical chemical and flow data collected from 1983 through 1985 (Riley, 1990) are generally similar to data gathered during the current investigation, in 1998 and 1999 (CH2M HILL, 2000a). The timing, duration, and magnitude of discharge and loading peak events have remained very similar, except at certain locations in the Flood-Stanly Ore Body. The most dramatic observed difference was an increase in peak discharge in the Stanly crosscut (9SX), where maximum discharge increased from 30 to almost 400 gpm. However, as discussed in Section 3.3, this may be a result of the magnitude of runoff and the infiltration location in the West Fork Milo Creek, rather than in-mine flow path changes. A more thorough comparison of the historical to current data is presented in CH2M HILL, 2000a.

Lime demand in units of pounds per 1,000 gallons of water is the amount of lime needed at the treatment plant to neutralize the acidity and thereby significantly decrease the dissolved metals. Although lime demand was not analyzed in the historical work (1983–1985), lime demand was part of the analysis for the 1998-1999 data. Because the lime demand is highly correlated with zinc concentration in recent data, the lime demand of the historical data can be estimated. Zinc, in turn, is highly correlated with other major metals and sulfate, the major anion in the mine drainage. Table 1 illustrates the correlation among lime demand, zinc, iron and sulfate at 9LA during 1998-1999. The values represent pairwise Pearson linear correlation coefficients based on data collected during monitoring. There are 14 analyses in the data set. Similar significant correlations exist between these and other metals.

Table 2 lists the analogous correlations using the 48 pairs of analyses in the historical data collected during 1983 through 1985.

The correlations in parentheses for the historical data (1983 – 1985) in Table 2 are those calculated with only one outlier removed from the historical data. The correlations among metals in the historical data are excellent. However, the correlations between flow and metals are noticeably lower in the historical data than in the current data. The historical correlations are lower because when flows were changing, concentrations were not. The change in concentration lagged behind the change in flow, and was accompanied by no measurable change in flow. This is illustrated and presented more fully in the discussion of hysteresis that follows.

Figures 2 and 3 illustrate graphically the strong correlations between flow (Q), zinc, iron, sulfate and lime demand (LIMED in the current and historical data sets, respectively). The bar graphs are frequency histograms that illustrate the distribution of data for a given variable. The significant linear correlations indicate that essentially any of these parameters can be used as an indicator of overall metal content. However, zinc, with its elevated concentration, conservative nature in the acid mine water, and strong geochemical association with the other parameters (particularly cadmium), is selected to describe the overall chemical and flux characteristics in the mine water. Zinc also allows the combined use of the historical as well as the recent data.

The relation between discharge and zinc concentration at 9LA suggests that little or no acidic salts accumulate in the tributary flow paths from year to year. The hysteresis concept is discussed in Section 4.2. If substantial quantities of salts had built up and were in storage along the flow path, then the zinc concentration on the rising limb of the hydrograph would be higher at a given flow than on the falling limb. Figure 4 illustrates that little or no hysteresis effect is evident at 9LA. This indicates that only minimal quantities of salts accumulate underground during the drier seasons. An increase in concentration always occurs with an increase in discharge. Likewise, a decrease in concentration is associated with a decrease in discharge. Some of the zinc concentrations on both the rising and falling limbs are different for a given discharge rate. However, for others the concentrations on the two limbs are similar and this suggests that there is not time between significant flow events for a sufficient accumulation of soluble metal from either oxidation or ponded water. Alternately, one or more of the upgradient-contributing source areas of the mine do not participate in the significant increase in flow.

An examination of the zinc concentration and discharge at 9LA for separate years reveals more clearly the lack of a strong hysteresis effect. Figures 5 and 6 present zinc concentration and discharge data for calendar years 1984 and 1985, respectively. Insufficient zinc concentration data on the rising limb exist for 1983 to present, for all limbs for that year.

The results from 1984 exhibit limited separation between the limbs of the hydrograph. Rather than a hysteresis effect, results suggest a simple linear relation between discharge and zinc concentration. The rising and falling limbs cross, suggesting that a substantial amount of acidic salts were not available for mobilization during spring runoff. The first data point on the rising limb of the hydrograph is associated with no increase in zinc concentration. The increase in discharge comes from tributary sources that have relatively good water quality, with zinc concentrations generally from 10 to 100 ppm. Subsequent data points on the rising limb show an increase in zinc concentration in response to contributions from sources that discharge very poor-quality water, with zinc concentrations up to 17,000 ppm, and have low discharges, while the earlier clean discharges have tapered off.

The results from 1985 (Figure 6) exhibit greater separation between the limbs than did those from 1984. The maximum zinc concentration occurred on the rising limb. However, the rising limb generally has lower zinc concentrations than the falling limb at a given discharge rate. This suggests little or no accumulation of acidic salts underground during the annual drier season. The contributions of tributary sources to 9LA with markedly different water quality are illustrated strongly in Figure 6. An increase in discharge of approximately 160 gpm is accompanied by a decrease in zinc concentration at the beginning of the rising limb of the hydrograph. Subsequent data points on the rising limb show a very modest increase in discharge that is associated with a dramatic increase in zinc concentration. This pattern is very similar to that in 1984 and suggests the hydraulics for clean water flow versus poor-quality water flow behaves in a consistent manner.

The early increase in discharge comes largely from 5BK, 5WM, and the old Reed Pump Back system. Together, they account for 80 percent of the observed increase in discharge. They all produce fairly good-quality water.

The sharp increase in zinc concentration is associated with no measurable change in discharge. The tributary sources that are responsible for the increase in zinc concentration all drain the Flood-Stanly Ore Body, and contribute only a small amount of discharge. The locations that contribute to the increase in concentration are 9SO, 9SX, and the old 7 Level drain system. The aggregate change in discharge from these locations between the sampling events was 24 gpm, well within the measurement error at 9LA. Zinc concentrations from these locations reached up to 14,000 ppm.

The responses at 9LA suggest the following:

- A strong hysteresis effect from the dissolution of acidic salts is not evident, although the sampling frequency of two to three times per month was too infrequent to demonstrate or to definitively refute a hysteresis effect
- The contribution of tributary sources with markedly different water quality occurs with an observable time lag
- A very substantial change in water quality can be associated with very little change in discharge

Examination of tributary monitoring stations to 9LA station demonstrate very different relations between zinc concentrations and discharge rates at various sites that drain the Flood-Stanly Ore Body. For example, Figures 7 and 8 clearly show that zinc concentrations do not change much with discharge ranging from 50 to 500 gpm at the 9SX station in either the historical or current data sets. The data all fall within a typical analytical error band of plus or minus 10 percent.

In strong contrast to 9SX, zinc concentration decreases as discharge increases at 9SO as shown on Figure 9. These relationships also show little hysteresis between rising and falling limbs of the hydrograph. The linear least square fit equations for the historical and current zinc concentrations in milligrams per liter (mg/L) based on natural logarithm of flow are essentially the same:

Historical: Zinc (mg/L) = 18,200 – 3,720 * Ln Flow (r=0.88)

Current: Zinc (mg/L) = 18,500 – 4,000 * Ln Flow (r=0.95)

The lack of hysteresis and close similarity between the historical and current data strongly suggest that there is little to no storage of oxidation products or mine pools in the flow path of this part of the Flood-Stanly Ore Body. Furthermore, even though the flow at 9SO is significantly lower than the flow at other stations, the pH is significantly lower and metals concentrations significantly higher at this location than at any other measuring station. This location would have been the location expected to show a major hysteresis effect because of

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its low base flow and apparently relatively long flow path. The zinc-flow relationship indicates that this water is being diluted (decreasing metals concentration) with increasing flow (increasing infiltration). Nevertheless, zinc loading and therefore lime demand increases with increasing flow because the discharge rate increases more than the concentration decreases.

Zinc loading at 9LA integrates the majority of flows and metal contributions from the gravity drainage on the Milo Creek side of the mine. The characteristics represent a very diverse mixture comprised of relatively excellent quality water from drill holes and fracture drainage from the subregional groundwater system, which combines with highly acidic drainage from the Flood-Stanly Ore Body (9SO, 9SX etc.).

Figure 10 shows that a strong linear relation exists between zinc load and collective discharge at 9LA. The data presented are those collected from 1983 through 1985 because there are so many more observations on which to establish a relation. As discussed previously, the 1983 through 1985 and the 1998 and 1999 data at this location are similar. The zinc load increase is tightly correlated with the increase in discharge rate. In addition, the rate of increase in zinc load is approximately 10 times the rate of increase in discharge. For example, as discharge increases from 400 to 600 gpm, the zinc load increases from 1,600 to 3,600 pounds per day.

Extrapolation of the data to the X intercept suggests that approximately 250 gpm of the discharge carries no metal load at all. This is confirmed by measuring drill hole discharge and other regional groundwater sources that consistently have relatively good to excellent quality water (pH near and above neutral and very low metals concentrations). For example, the drill hole on 7 Level discharges between 150 and 170 gpm, and drill holes on 5 Level discharge 60 to 90 gpm. The drill hole on 7 Level discharges water that has a pH between 3 and 5, and zinc concentration between 0.1 and 1 ppm. The 5 Level drill holes discharge water that has a pH between 3 and 7, and zinc concentration between 0.02 and 0.2 ppm.

The relation between zinc loading and discharge strongly suggest two concepts. First, a decrease in recharge on the West Fork Milo Creek side of the mine will likely result in a decrease in zinc loading at 9LA. This is largely because recharge to the Flood-Stanly Ore Body comes mostly from the West Fork Milo Creek basin. Second, the zinc loading at 9LA is clearly a result of mixing of originally very good-quality water with highly acidic metal-bearing water. Remediation that restricts excellent-quality surface water from infiltrating into the Flood-Stanly Ore Body should significantly reduce the amount of elevated metal concentrations and acidic water created by this infiltration. Additionally, both reduction and segregation of the water that flows from the Flood-Stanly Ore Body, and that from the subregional groundwater system, would result in reduced precipitation and accumulation of metal hydroxides created by their mixing within the mine, and would thereby decrease mine maintenance (mucking out of accumulated metal hydroxides). Because the two water sources are spatially separated, perhaps the in-mine separation of these two may be feasible and cost-effective.

4.4 Buildup of Efflorescent Salts as a Reservoir of Metals

The buildup of efflorescent salts within the mine is a potentially negative result of recharge reduction efforts. Such a buildup could provide the basis for a large metal load in the future during a period of high precipitation. However, buildup of sufficient quantities of salts at the Bunker Hill Mine to create a significant reservoir of soluble metals seems fairly unlikely. Salt accumulation in any of the accessible portions of the Flood-Stanly Ore Body or surrounding workings has not been observed. What is much more common at the Bunker Hill Mine is the development of numerous pools of poor-quality water in undulations in the drifts, behind yellow boy (predominantly iron oxyhydroxide precipitate) and constructed dams, and in plugged transfer raises. The ponds constitute a reservoir of poor-quality water but less of a reservoir than metals-bearing salt deposits. Furthermore, the water chemistry at 9SX, 9SO, 9VR and 9CR do not indicate that reservoirs of soluble salts are building up along their respective flow paths into the mine under historical and current conditions. There is a relatively high correlation between historical and current metal concentrations and, therefore, lime demand. Salt buildup, if it were occurring, should have become evident in these relationships. Inspection for salt buildup (where accessible) and monitoring of water flow and quality underground are critical components of recharge reduction measures. Data generated as a result of monitoring will allow assessment of potential buildup of salts within the mine.

5.0 Risks/Uncertainties

As with any work involving relatively complex inter-related natural and anthropogenic surface water/groundwater conditions, there are always uncertainties and associated risks. However, given what is described in the preceding text, reduction of recharge to the Bunker Hill Mine should result in a decrease in lime demand and associated sludge generation. There is uncertainty in the amount of decrease that will likely occur and, therefore, the effectiveness of the mitigation efforts. Furthermore, there is uncertainty whether or not recharge reduction efforts will result in sufficiently large soluble metal precipitate accumulation and subsequent release at a future high flow event. However, even if salts do accumulate and are released by a large flow event, there is a sufficiently large storage volume in the mine for retention of essentially any foreseeable future high flow event (under current mine management conditions), although the capability of capturing and storing these high flows must be constructed, demonstrated, and maintained. Also, a treatment plant could be designed to handle flows and concentrations of concern. The following text provides a more thorough discussion of risk and uncertainty questions.

5.1 Recharge Reduction Mechanisms and Effectiveness

Water flow within the mine occurs primarily through man-made openings under partially saturated conditions. Flow is along the bottom of drifts and inclined shafts. Only a very small percentage of the upper country workings are flooded and these are behind local dams. Water movement through open and backfilled stopes is under unsaturated to partially saturated conditions. Historical and current data show that the dominant infiltration events to the mine coincide with the spring snowmelt period. Water flow is much higher during this period than during the remainder of the year. In fact, the flow in the mine decreases throughout the remainder of the year, much like a recession pattern in a groundwater-fed stream.

Acid salts are formed at reaction sites where they remain until washed into the water flow system within the mine by infiltrating surface water. Pools of acidic water form in drifts, particularly where yellow boy deposition is common. In many cases the reaction salts and pools of acid water remain in place until there is a flushing effect from recharge, generally related to snowmelt infiltration. The data of flow versus lime demand at the 9LA site show an approximately linear relationship between these factors. The higher metal concentrations at higher flow result from the flushing of soluble metal salts and acid water from the mine workings.

A reduction in recharge to the underground workings would act to reduce both the high flow surge of water in the mine and the low flow component. Research results from sites at the end of the New East Reed drift on 5 Level show that near-surface fracture systems effectively “fill up” during the spring recharge event and drain to the mine throughout the rest of the year.

A recharge reduction program that is targeted at the West Fork Milo Creek drainage has a high potential to decrease the surface water infiltration responsible for the flushing / washing effect within the Flood-Stanly Ore Body. Obviously, complete elimination of surface water infiltration and flushing / washing within this portion of the upper country would go a long way toward elimination of the Bunker Hill AMD problem, but it is unrealistic to expect complete elimination. The reduction in recharge to this portion of the mine through various recharge reduction measures is unknown. However, the effectiveness of recharge reduction efforts in this area should be high rather than low simply because the configuration of the drainage relative to the ore body leads to this conclusion. All aspects of the geology and hydrology that have been investigated support the likelihood of success using this approach.

5.2 Potential for a Significant Acid Water Release at a Future High Flow Event

The question has been raised whether installation of recharge reduction facilities, particularly in the West Fork Milo Creek drainage, would lead to a significant storage and release of metals at a future high flow event. Such an event might be triggered by the following conditions. First, the recharge reduction facilities might greatly reduce the annual surface water recharge events. Second, without the annual flushing / washing events, acid salts might continue to build up and store soluble metals available for mobilization in acid water at a later high-flow event. Third, a run-off event might occur that greatly exceeded the capacity of the recharge mitigation options, or the mitigation could fail. Fourth, this flood event in the underground would flush the accumulated acid salts in an extreme event that could exceed either storage or treatment capacity.

This scenario is dependent on several conditions that would require a considerable number of inter-related conditions to be present and events to occur. The first question is whether, in the absence of frequent flushing / washing events, acid salts would continue to build up. There have been considerable changes in the mining activities and seasonal flow conditions incorporated in the historical and current flow and chemistry data. These data do not indicate a recognizable salt buildup. Furthermore, the high flow event would have to have both significantly higher flow and, more importantly, duration to exceed the storage or treatment capacity. A sufficiently large metal-bearing salt buildup would probably take several years to accumulate, during which time monitoring at historical sites should measure and provide both considerable warning of the buildup rate and allow response prior to a release. Also, the extreme flood event scenario might also be eliminated by redundant recharge mitigation options.

Another question deals with how water might move through the underground workings during an extreme high recharge event under both present conditions and under future conditions where flow underground is modified. Prediction of future flow through the mine involves more open-ended questions and necessary assumptions than just the question of reduced lime demand and sludge production by reducing the surface water infiltration into the mine workings. There are far too many unknowns to allow speculation before an estimate is attempted through further investigation. Future mine management must be the first defined condition for such an estimate.

6.0 Recommendations to Fill Data Gaps and Minimize Uncertainty

The present understanding of water flow and acid production from the Bunker Hill Mine has resulted from surface and subsurface research efforts both in the 1970s and 1980s by the University of Idaho, and in the recent efforts. The classic approach to hydrogeologic investigation is to physically change the hydraulic characteristics of the system and observe the response patterns. This approach is the optimum way to gain additional understanding in order to respond to the questions raised in the previous section.

Construction of a first stage or several related stages of mitigation options in the West Fork Milo Creek drainage is needed to collect data on the effect of reducing infiltration through the Flood-Stanly Ore Body. This should include monitoring of both surface water and mine water / metals concentrations / lime demand response.

Flow and quality monitoring in the underground workings is essential for assessing mitigation performance and to further the understanding of the mine water. Cooperation with the mine owner / operator is essential.

Measurement of stream flow within the potential recharge areas is necessary to assess the effectiveness of recharge reduction mitigation options. At present, the potential for recharge-related savings from the mitigations is based on runoff estimates but not field data, because stream flow measurement sites do not exist.

7.0 Cited References

Balistrieri, L.S., Box, S.E., Bookstrom, A.A., and Ikramuddin, M. 1999. Assessing the Influence of Reacting Pyrite and Carbonate Minerals on the Geochemistry of Drainage in the Coeur d'Alene Mining District. Environmental Science and Technology. Volume 33. pp. 3347-3353.

NEXT

CH2M HILL, 2000. Supplement No. 1B, Bunker Hill Mine Conceptual Model, Final Data Summary for 1998 / 1999 Monitoring Program, Bunker Hill Mine Water Management Project, Kellogg, Idaho. February. CH2M HILL, Spokane Washington.

CH2M HILL, 1999a. Bunker Hill Mine Water Presumptive Remedy; prepared for U.S. Environmental Protection Agency.

CH2M HILL, 1999b. Acid Mine Drainage – Bunker Hill Mine Water Conceptual Model; prepared for U.S. Environmental Protection Agency.

Eckwright, T.A., 1982. Water Flow Patterns within the Bunker Hill Mine, Idaho: M.S. Thesis, University of Idaho, 56p.

Erikson, D.L., 1985. Analysis of Water Movement in an Underground Lead-Zinc Mine, Coeur d'Alene Mining District, Idaho; M.S. Thesis, University of Idaho, 115p.

Hobbs, S.W., Griggs, A.B., Wallace, R.E., and Campbell, A.B., 1965. Geology of the Coeur d'Alene District, Shoshone County, Idaho: U.S. Geological Survey Professional Paper 478, 139 pp.

Hunt, J.A., 1984. Analysis of Recharge to an Underground Lead-Zinc Mine, Coeur d'Alene Mining District, Idaho: M.S. Thesis, University of Idaho, 91p.

Kroll, E.H., 1935. A mineralogic study of the Bunker Hill lode at Kellogg, Idaho, B.S. thesis, University of Idaho, 16 pp.

Riley, J.A., 1990. A Comparison of Multivariate Statistical Analysis and the Use of an Indicator Ion for the Interpretation Water Quality Data: Ph.D. Dissertation, University of Idaho, 227p.

Trexler, B.D. Jr., 1975. The Hydrogeology of Acid Production in a Lead-Zinc Mine: Ph.D. Dissertation, University of Idaho, 164p.

TABLE 1
Correlation Among Iron, Zinc, Sulfate and Lime Demand
9LA Water Samples (1998 and 1999 Data)

	Discharge	Iron	Zinc	Sulfate	Lime Demand
Discharge	1.000				
Iron	0.992	1.000			
Zinc	0.946	0.936	1.000		
Sulfate	0.994	0.995	0.967	1.000	
Lime Demand	0.994	0.989	0.948	0.995	1.000

TABLE 2
Correlation Among Iron, Zinc, Sulfate and Lime Demand
9LA Water Samples (1983 through 1985 Data)

	Discharge	Iron	Zinc	Sulfate
Discharge	1.000			
Iron	0.661 (0.725)	1.000		
Zinc	0.662 (0.743)	0.973	1.000	
Sulfate	0.652 (0.721)	0.919	0.928	1.000

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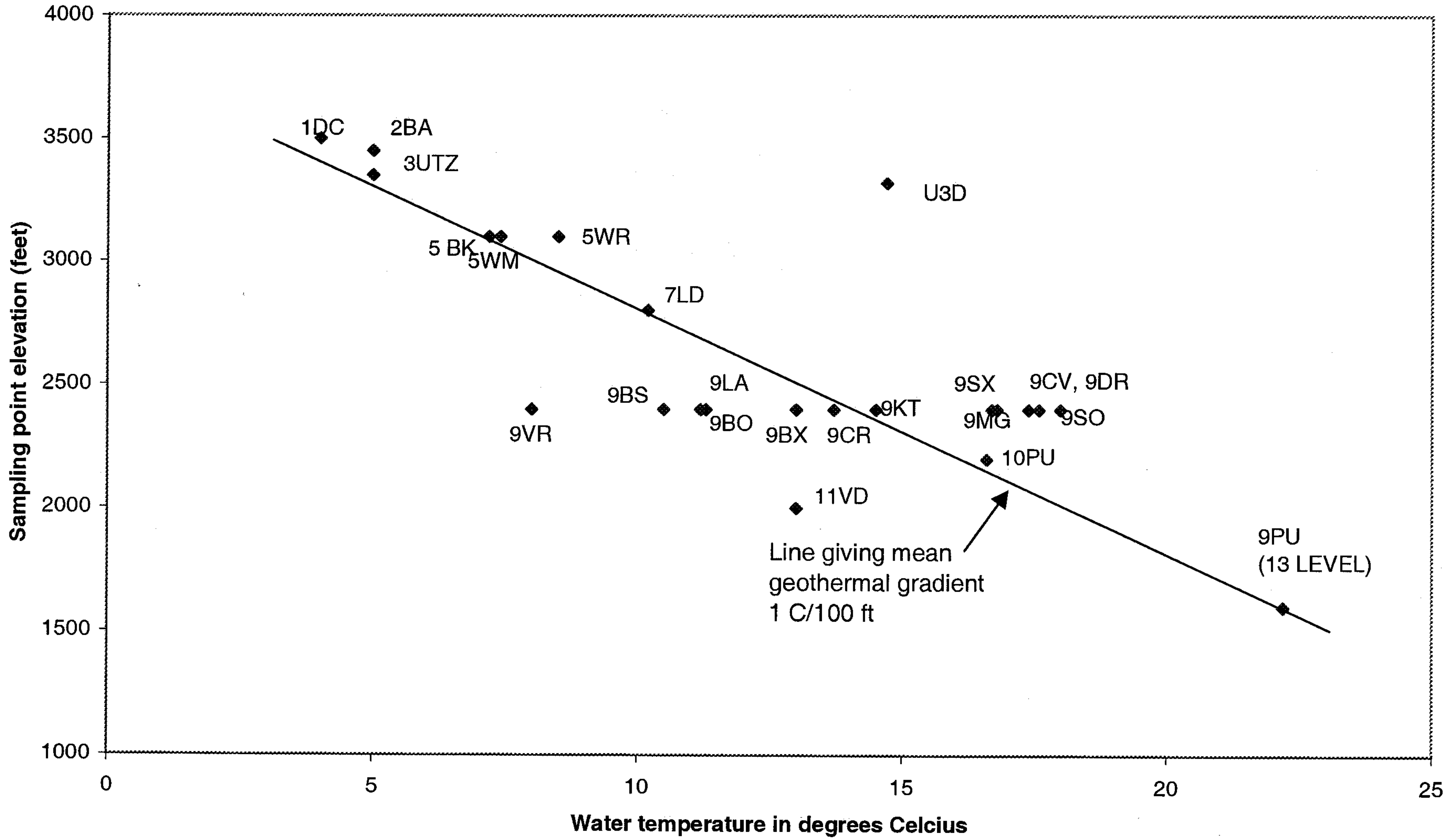
Figure 1
Average Water Temperature at Underground Sampling Sites, 1998-99 Data



9LA Current Correlations

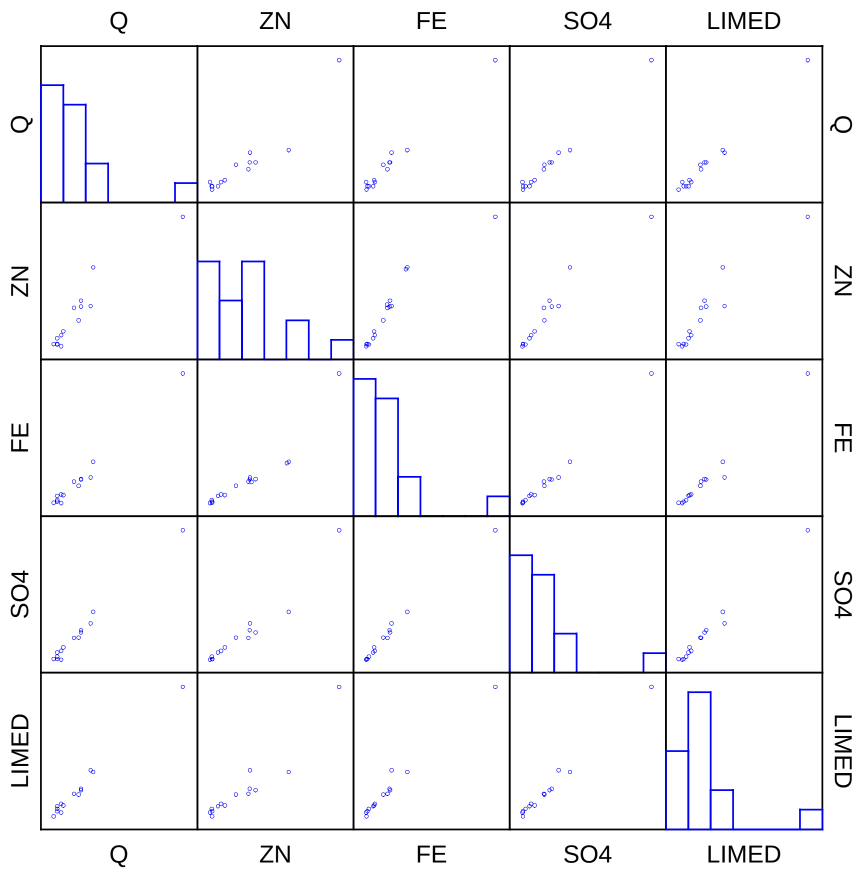


FIGURE 2
Correlations Among Selected Variables at 9LA (1998-1999 Data)

9LA Historical Correlations

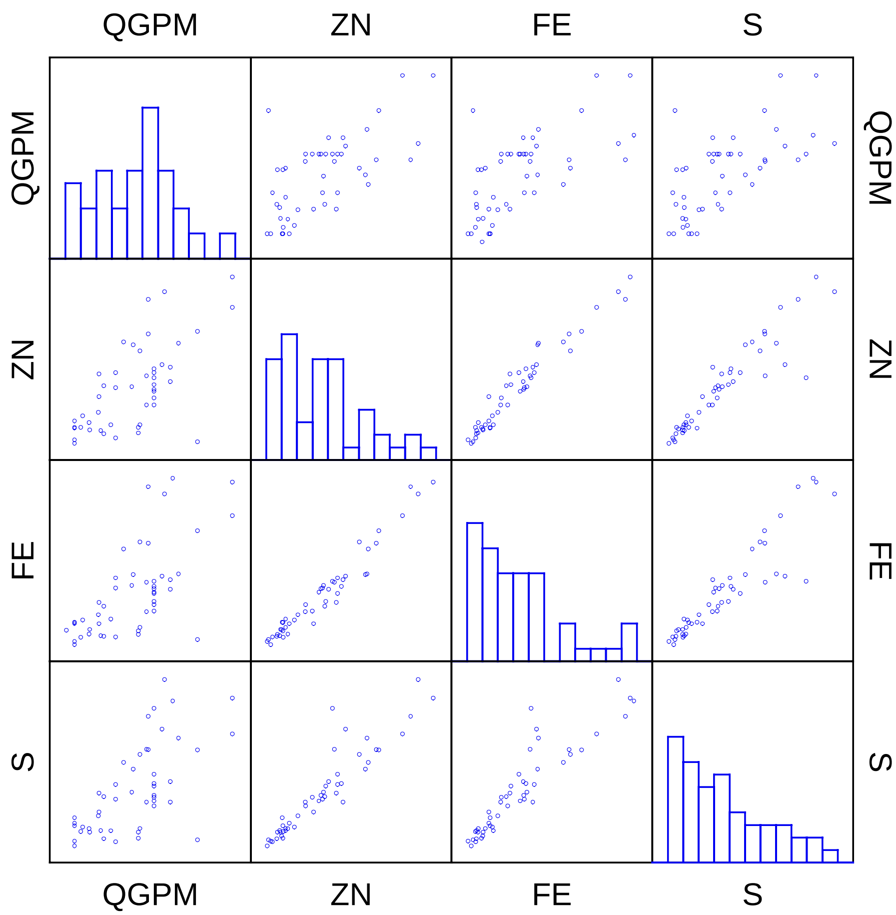


FIGURE 3
Correlations Among Selected Variables at 9LA (1983-1985 Data)

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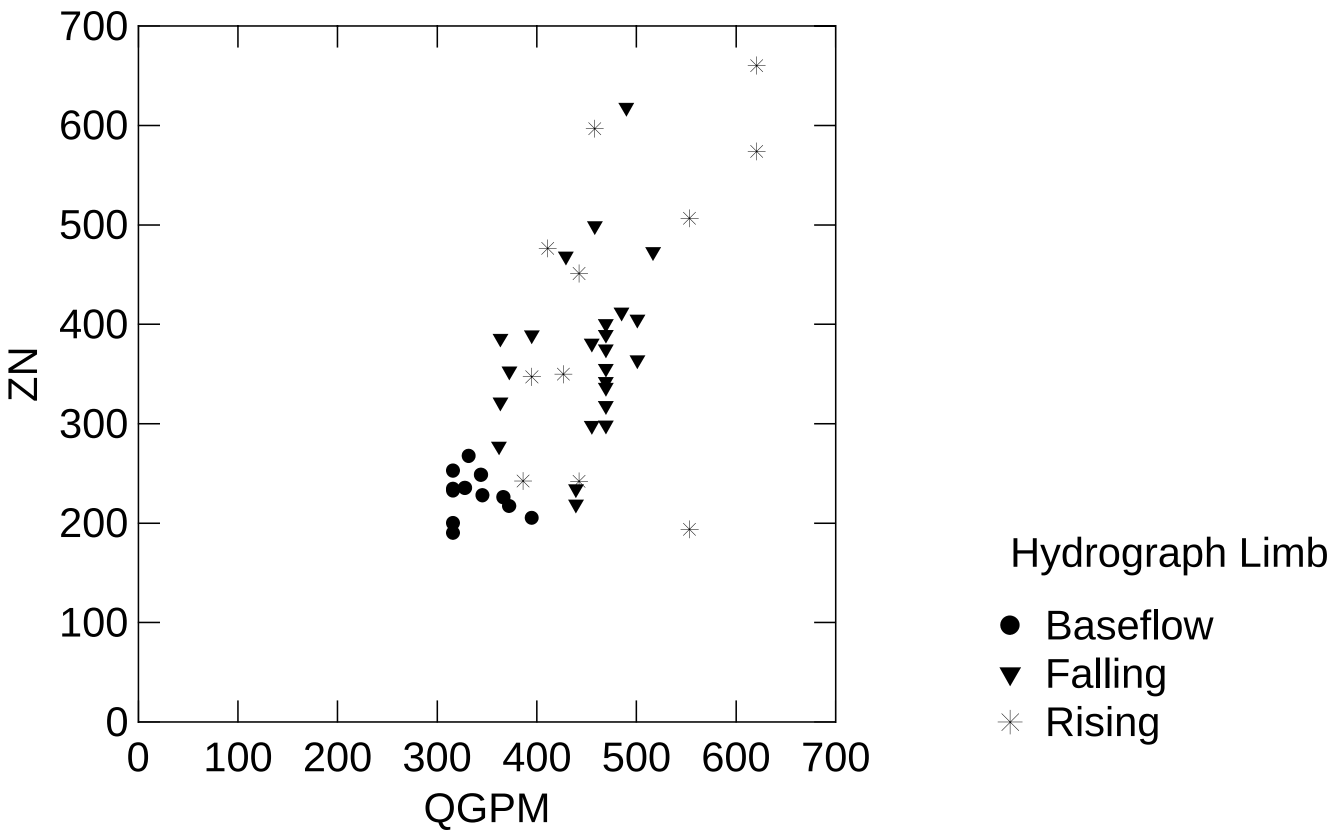

FIGURE 4
Relation Between Zinc Concentration (mg/L) and Discharge at 9LA.

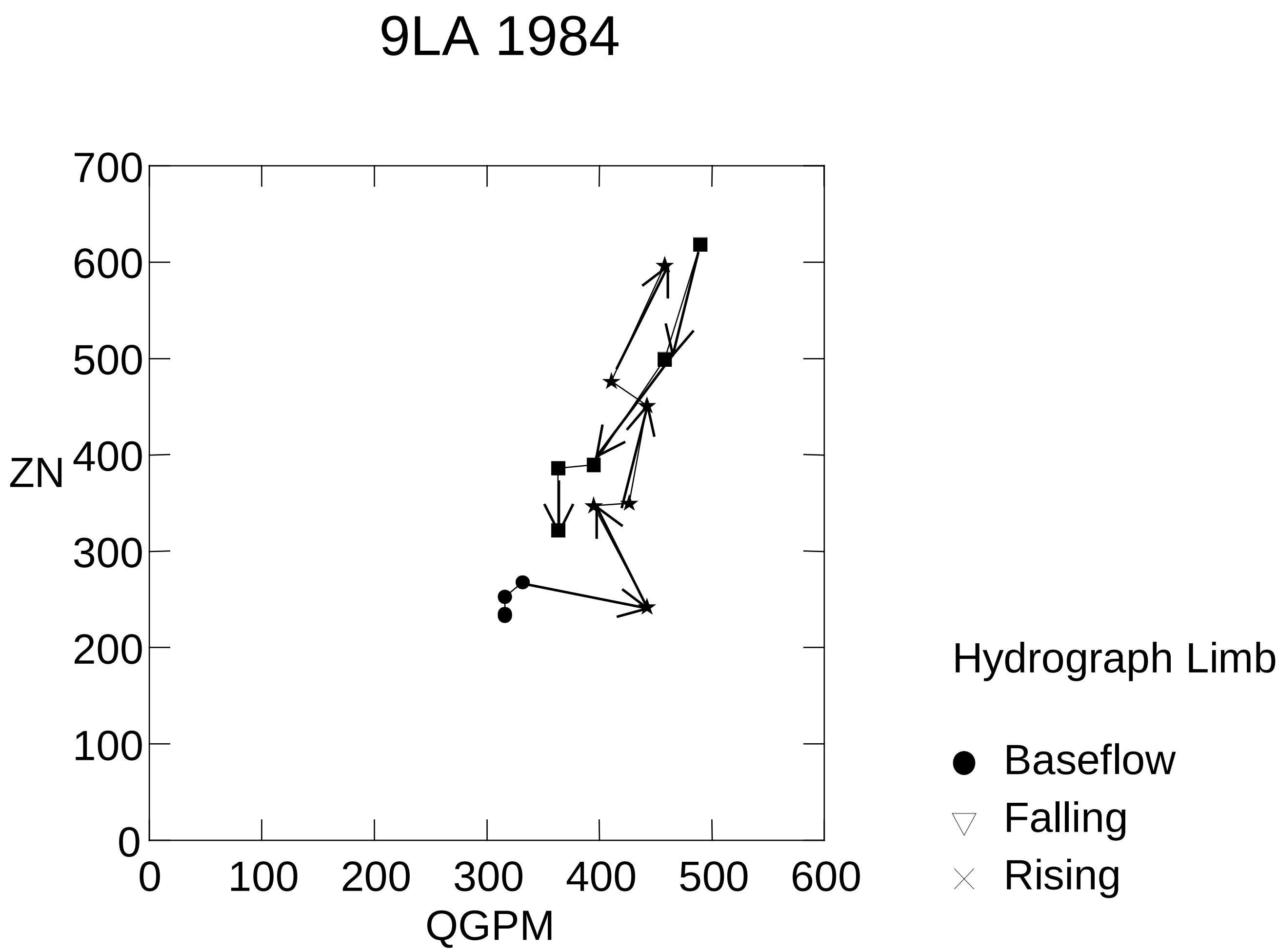

FIGURE 5
Relation Between Zinc Concentration (mg/L) and Discharge at 9LA (1984 Data)

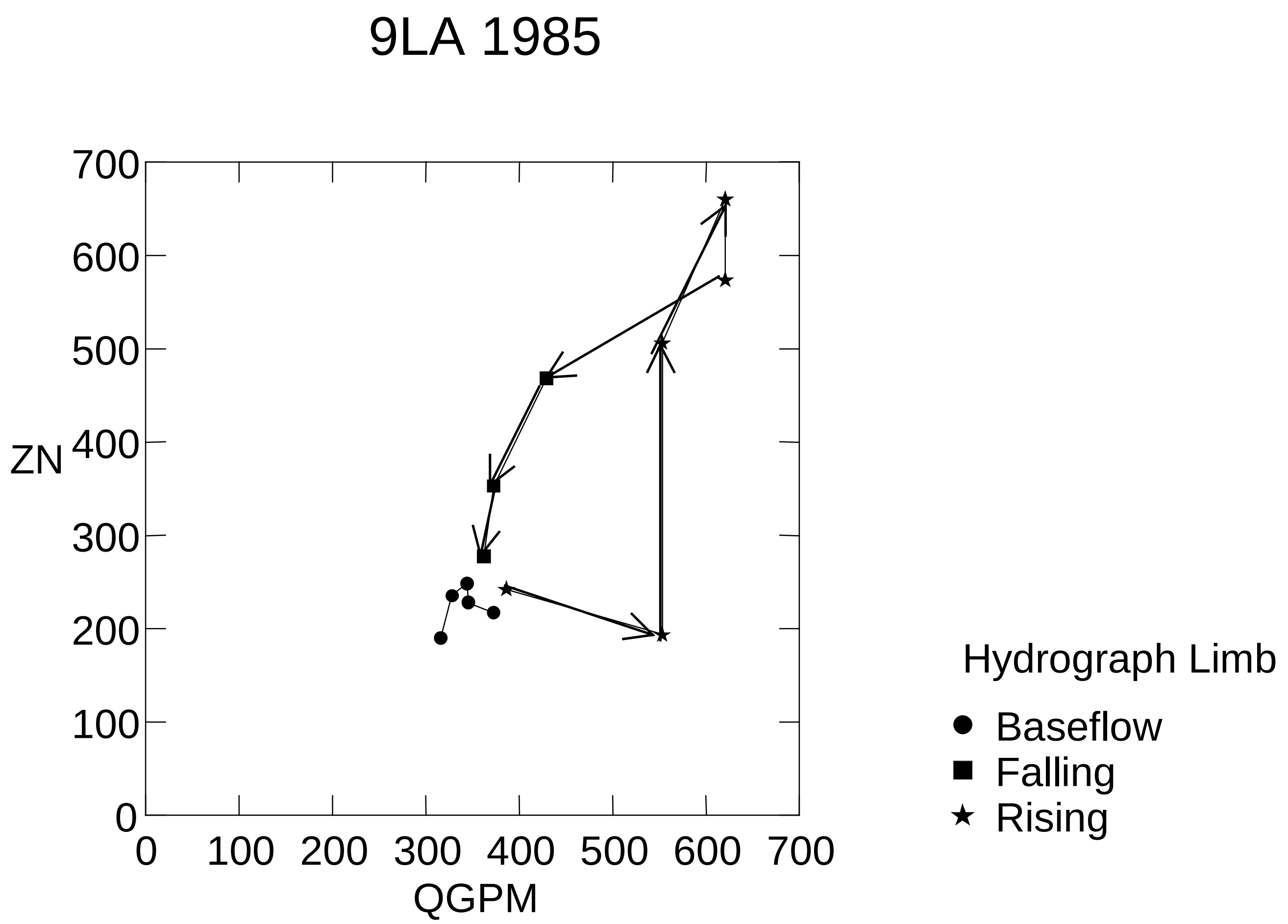

FIGURE 6
Relation Between Zinc Concentration (mg/L) and Discharge at 9LA (1985 Data)

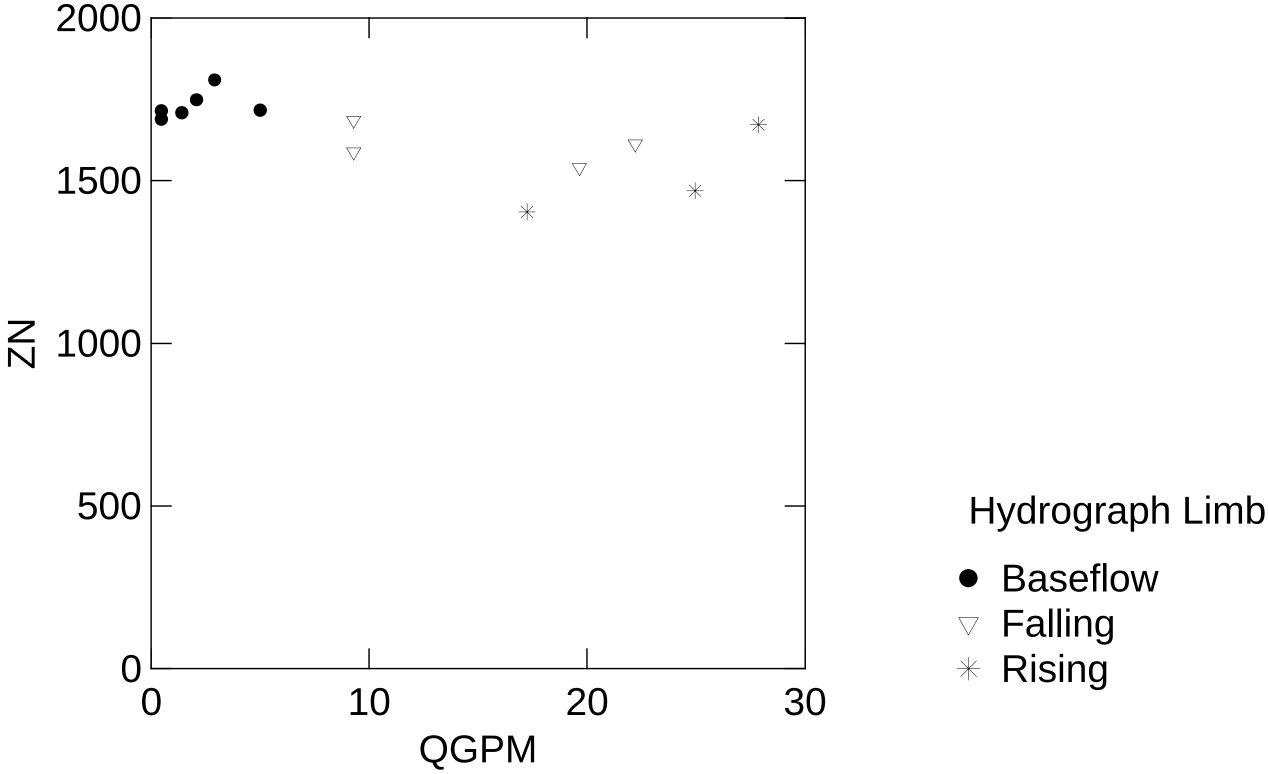

FIGURE 7
Relation Between Zinc Concentration (mg/L) and Discharge at 9SX (1983-1985 Data)

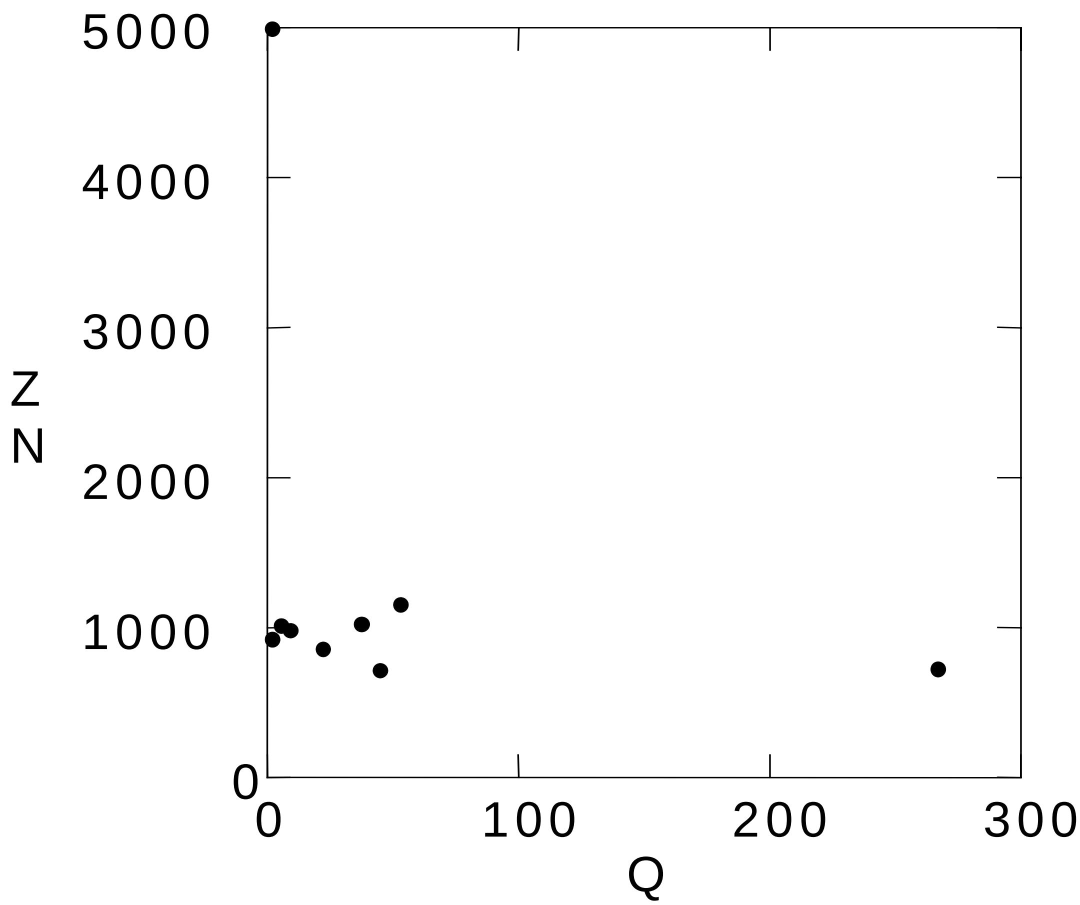

FIGURE 8
Relation Between Zinc Concentration (mg/L) and Discharge at 9SX (1998-1999 Data)

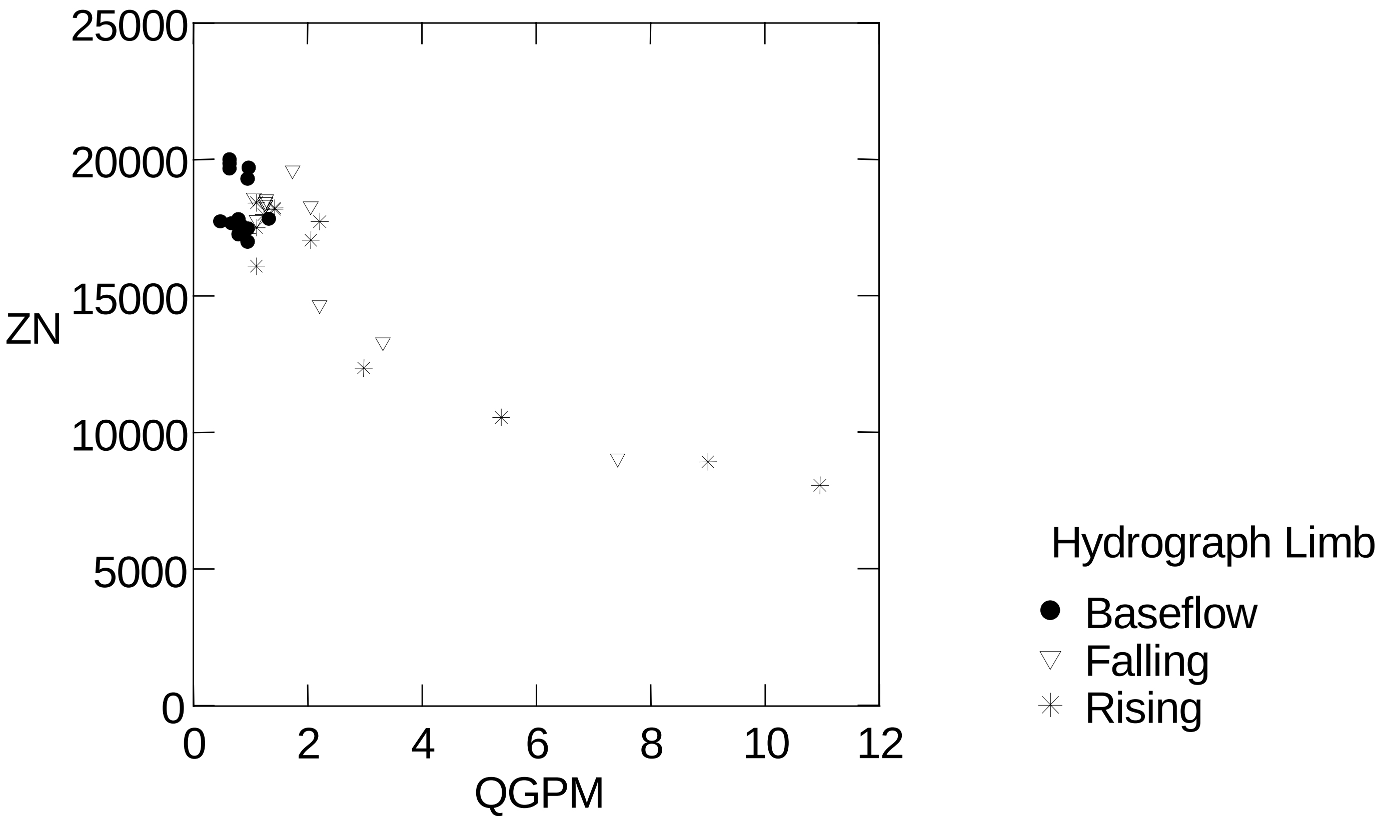

FIGURE 9
Relation Between Zinc Concentration (mg/L) and Discharge at 9SO.

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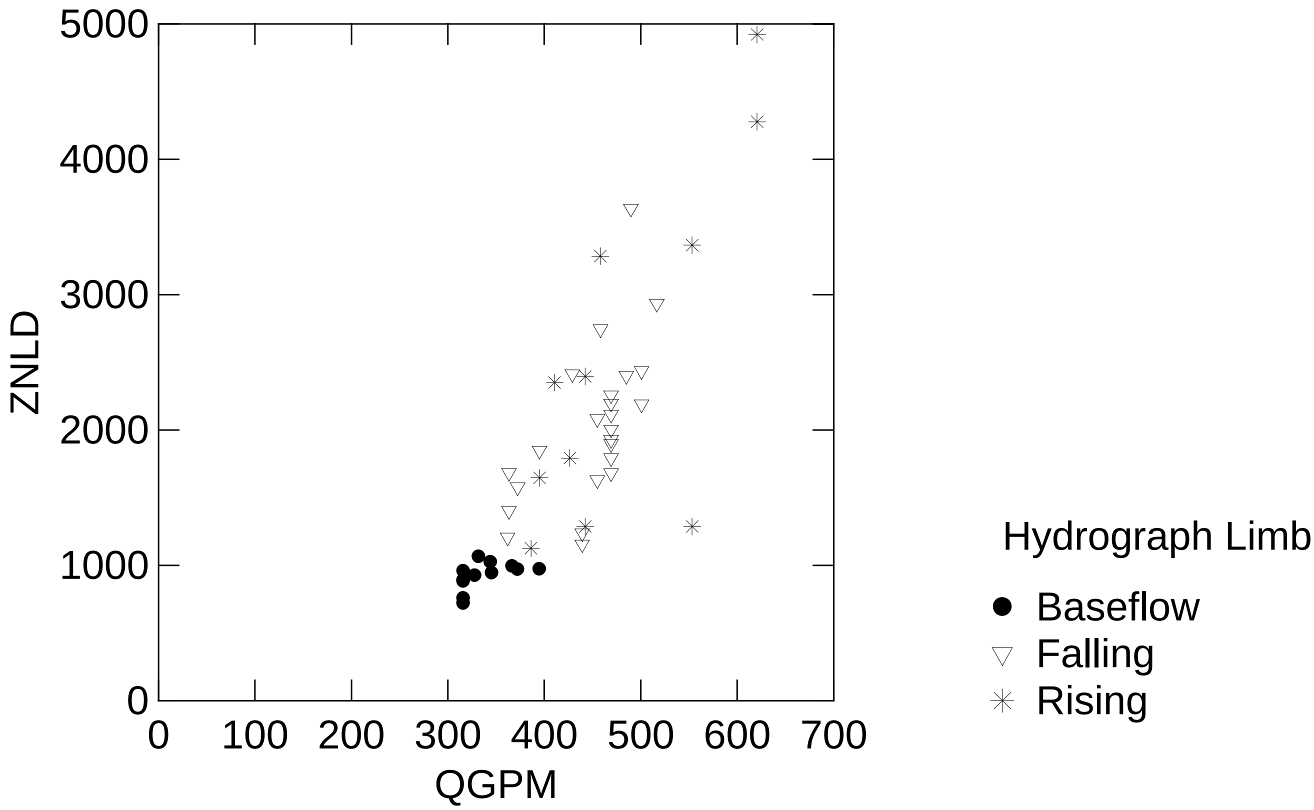

FIGURE 10
Relation Between Zinc Load (pounds/day) and Discharge at 9LA (1983-1985 Data)